ILLINOIS STATE WATER SURVEY
ATMOSPHERIC SCIENCES SECTION

ILLINOIS PRECIPITATION ENHANCEMENT PROGRAM
PHASE I

October 10, 1974

Interim Report

for

1 August 1973 - 30 June 1974

To

Division of Atmospheric Water Resources Management
Bureau of Reclamation
U. S. Department of Interior

Prepared by

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Co-Principal Investigators

Contract 14-06-D-7197

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ENHANCEMENT PROGRAM:
PHASE I: OCTOBER 10, 1974,
INTERIM REPORT FOR 1
AUGUST 1973 - 30 JUNE 1974.

Illinois State Water Survey

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WILLIAM C. ACKERMANN, CHIEF

October 21, 1974

Dr. Archie M. Kahan, Chief
Division of Atmospheric Water Resources Management
U. S. Department of the Interior
Bureau of Reclamation
Engineering and Research Center
Building 67, Denver Federal Center
Denver, Colorado 80225

Dear Dr. Kahan:

Enclosed is the Third Interim Report for the Illinois Precipitation Enhancement Program: Phase I. It covers the research activities pursued during the 1 August 1973 - 30 June 1974 period.

This report covers only the Atmospheric Sampling Program as approved in your letter of 10 August 1973. The FY-74 research activities are described. The project personnel are described in Appendix 1.

Sincerely,
ILLINOIS STATE WATER SURVEY

Stanley A. Changnon Jr.

Stanley A. Changnon, Jr., Head
Atmospheric Sciences Section
217/333-4260

SAC/rr
Enclosure

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INTERIM REPORT
1 August 1973 - 30 June 1974

Introduction

The aircraft measurement program carried out in June and July of 1973 was designed to determine the magnitude of a number of parameters considered to be important for the evaluation of the physical potential for the modification of warm season precipitation in the Central United States. Two factors of key interest were the efficiency of the coalescence process and the availability of latent energy that could be realized by induced freezing of liquid condensate. The analysis carried out during the past year was directed toward the eventual estimation of these two factors for the large number and wide variety of cumulus cloud systems probed during the 1973 airplane flights. It has concentrated on establishing the population statistics of the water substance in summertime clouds in central Illinois, in accordance with the overall program objectives set up in the original work plan for this phase of the Illinois Precipitation Enhancement Program.

This report presents a summary of the measurements of the bulk water which have been analyzed during the period of this report. The work is continuing and the sample will be materially enlarged as more flight data are processed.

The total condensate has been separated into estimates of the "cloud water", i.e., condensate in relatively small cloud droplets, and "precipitation water", the condensate in incipient or existing precipitation particles. (Throughout this report, the term condensate is used in its broadest sense and includes solid as well as liquid particles).

Basic Measurements

Three independent measurements were used in determining the partition of the total condensate into cloud and precipitation water content: (a) the total water content meter developed at the Naval Research Laboratory (Ruskin, 1967) which measures water in all phases, (b) the commercially available Johnson-Williams hot-wire liquid water content meter which, responds primarily to the cloud droplets, measuring little of the contribution to the condensate from solid particles and liquid particles larger than about 60 to 80 μm diameter (Barrett, 1958) and (c) the Cambridge Systems dewpoint hygrometer which measures the water-vapor content. The Johnson-Williams was mounted on the bottom of the housing for the total water meter and the entire assemblage was attached to the underside of the airplane wing well out of the region of

disturbed flow. A water-free air sample was introduced into the dewpoint hygrometer, which was located toward the rear of the airfoil.

An estimate of updraft and downdraft regions was obtained from the recorded output of a rate-of-climb meter. The particular instrument used (the IVSI, Teledyne Corp) incorporated a spring device to detect the initial vertical acceleration in addition to the normal differential pressure transducer. These measurements, in conjunction with those of aircraft pitch and angle of attack, permit a qualitative, and often semi-quantitive, estimate of vertical draft strength.

All the measurements were digitally recorded every half second on computer compatible magnetic tape. The total water meter has very short response time and has space resolution of 2 or 3 m. In order to minimize the possibility of bias arising from the sensing of single large drops, the current was electronically linearized and averaged over an interval of 0.5 sec.

The details of the aircraft instrumentation were given in the Interim Report covering the period from 1 July 1972 - 31 July 1973 (Ackerman, 1973).

The Data Sample and Analysis Approach

The data sample presented here was collected on five flights in Southwestern Illinois and Eastern Missouri. The measurements were made at 600 mb ± 20 mb (approximately 4450 m MSL). Except in a few cases cloud bases were at 1200 to 1300 m MSL and most clouds topped out between 5200 m and about 7000-7500 m at the time of cloud penetration. All of the clouds in the sample were visually classified as vigorous before entry. Penetrations were into a variety of cloud types: cumuliform tower families which merged into Cumulonimbus Calvus; Cumulus Congestus associated with Cumulonimbus, both in clear areas and imbedded in Altostratus-Altocumulus layers; young Cumulonimbus Calvus, and in a few instances young thunderstorm cells (Table 1).

The measurements indicate considerable horizontal variability in the internal structure. Some examples of the cloud data are shown in Figs. 1-3. These data have been smoothed either by a 5-point running mean providing averages over about 200 m or by consecutive averaging over three data points (120 m). In interpreting these graphs it is important to bear in mind that the response characteristics of the various instruments differ significantly. The Rosemount platinum resistors thermometer and the two water meters have rapid response. The response time of the dewpoint hygrometer, from which vapor density is determined, is close to 2 sec. The airplane itself is the sensor for measurements of vertical velocity. Although the initial change due to entry into a vertical draft is sensed rather quickly by the IVSI the inertia of the aircraft of the Aero-commander results in a response time of the order of 5 to 10 sec. Thus, a draft may be indicated in the airplane rate-of-climb for some seconds after the plane has left it.

Table 1. Flight Information.

Flt No.	Date / Time(CDT)	*General Weather* / Cloud Type	No. of Cloud Units: All	No. of Cloud Units: $W_T > W_A$ (1)
5	6/14/73 1510-1810	*Air Mass Showers* Cu Cong; Cb Calvus; Cu Twr family merging into Cb Calvus.	39	11
11	6/30/73 1530-1745	*Air Mass Showers* Cu Cong and Cb Calvus in a group of shower clouds.	14	3
17	7/9/73 1345-1615	*Squall Lines* Cu Cong family; Cu Cong vcty Tstm; Cb Calvus; "back feeders" to large Cb(2).	32	1
18	7/9/73 1730-1930	*Squall Lines* Cu Cong vcty Tstm; Isol twrg Cu; Tstm cell in bldg stage; "back feeders" to large Cb.	19	2
20	7/14/73 1600-1800	*Post cold frontal passage with over-running* Cu twrs and Cong imbedded in multiple cloud layers; Cu Cong vcty Tstm; Tstm cell.	19	3

(1) W_T = average total condensate for cloud unit
W_A = "adiabatic" liquid water content = theoretical parcel water content with no dilution or precipitation

(2) Cumulus towers close to the rear side of large thunderstorms which, in a relative short span of time, become part of the main trunk of the storm.

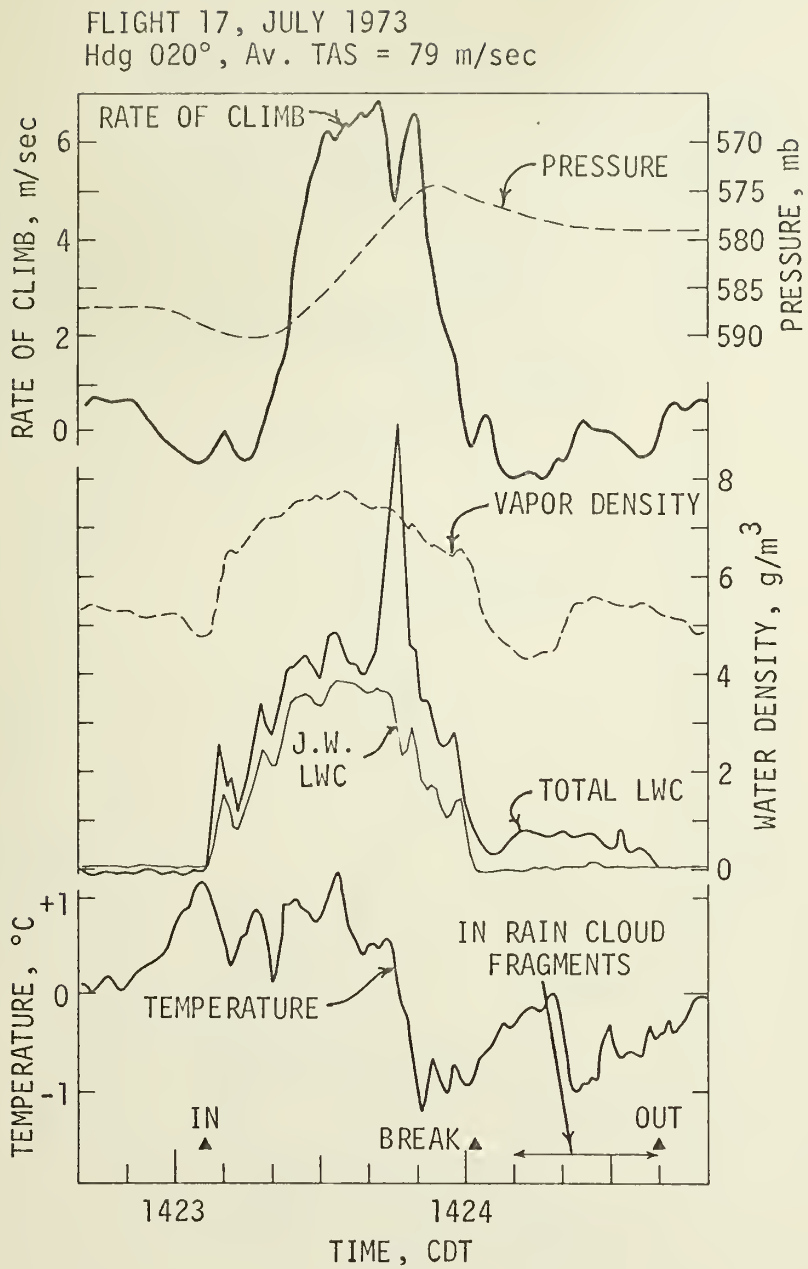

Figure 1. Variations of several cloud parameters during a penetration through a vigorous, broad cumulus congestus. Data smoothed by 5 point running mean (about 200 m).

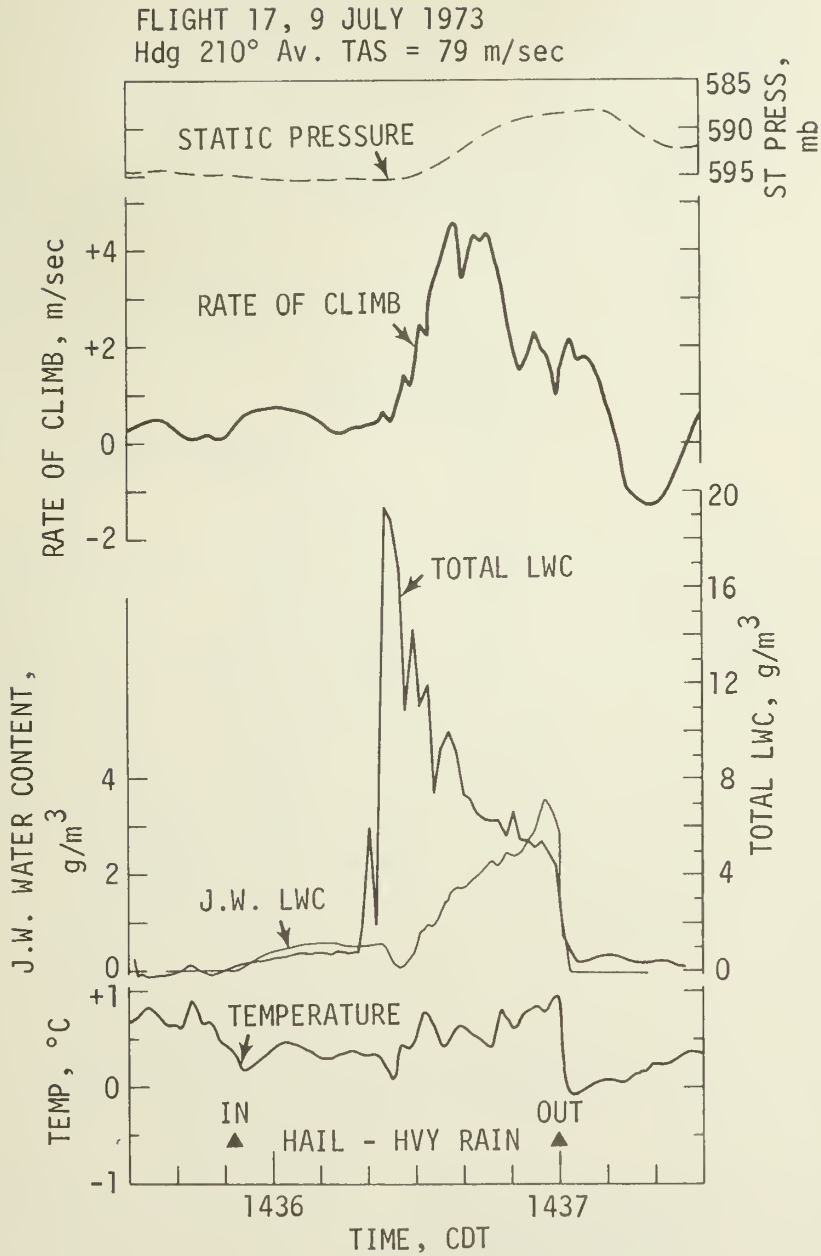

Figure 2. Variations of several cloud parameters during a penetration through a "precipitating" but still growing cloud. Note the differences in the scales of the cloud and total liquid water contents. Data averaged over 120 m.

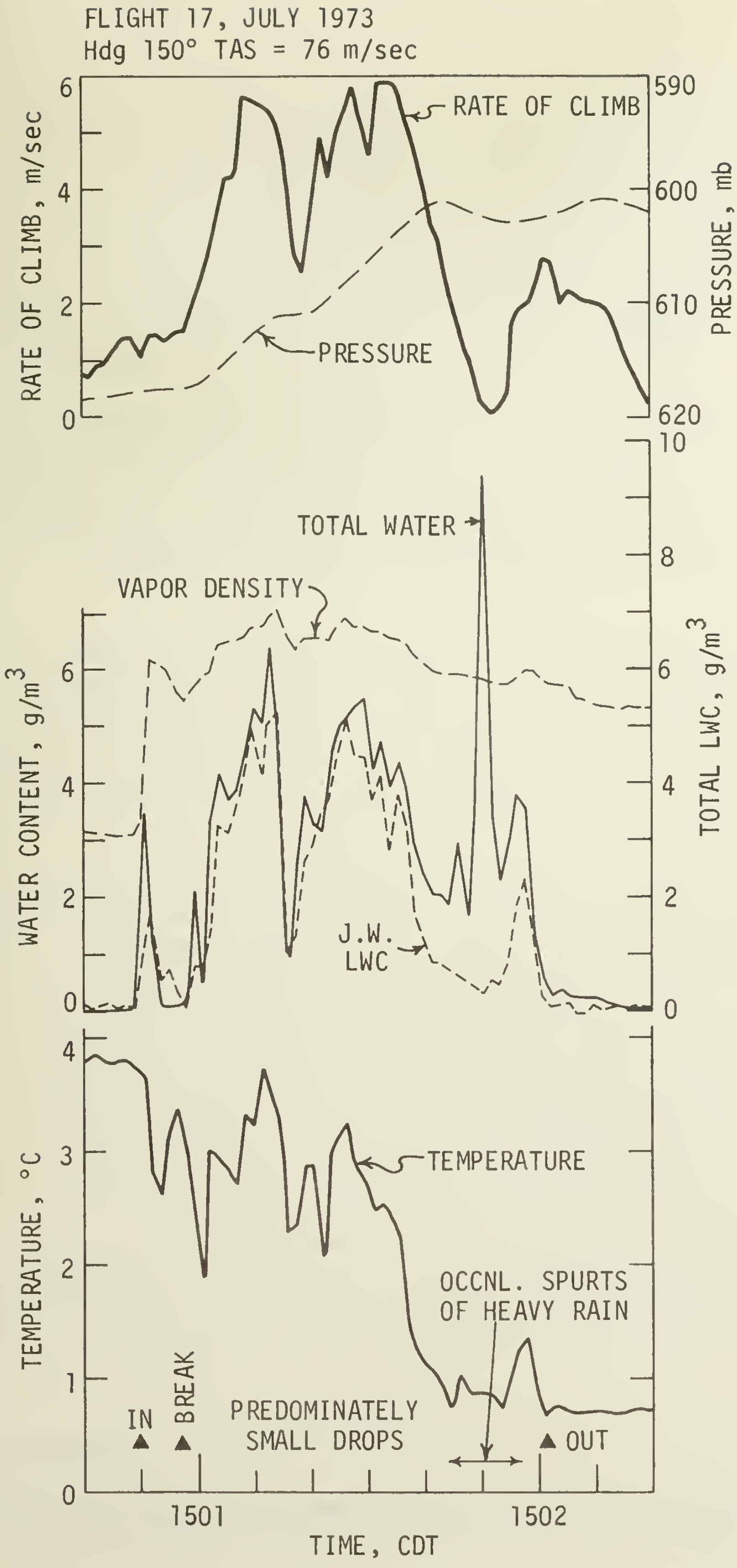

Figure 3. Variations of several cloud parameters through a growing, multi-cellular cloud. Data averaged over 120 m.

In Fig. 1 are shown the measurements from a penetration through a cloud in which the structure is relatively simple. Although there is some small scale structure, the space distributions of most parameters are fairly smooth and symmetrical. The most notable exception is temperature but, as shown in the figure, the variations include those due to altitude changes as well as in-cloud space changes. Indeed, because of the change in altitude, the variations in all parameters include cloud variations in the vertical as well as the horizontal. The precipitation water (the difference between the total liquid water and the cloud LWC) appears to be fairly uniform at about 1 gm/m^3 except for a narrow rain shaft on the NNE side of the cloud.

It is not the intent here to explore the details of particular clouds. However, the dry, warm areas adjacent to the cloud edges, are of particular interest to the author. Some years ago she reported on the presence of this phenomenon adjacent to cumulus towers in East Central Texas (Ackerman, 1969) and speculated that they must be due to descending motion around the cloud periphery. The observation around this particular tower tend to support this conclusion.

The main rain shafts sometimes occurred in the center of the cloud and sometimes on an edge, as in Fig. 2. In most cases, when the total water was very large, the cloud water was small. Despite the tremendous asymmetry in the distribution of water, the structure of this cloud is still moderately simple, although the variation in rate of climb suggests that the updraft as well as the water might have been "multi-cellular" lower in the cloud.

The horizontal structure of most of the clouds was considerably more complicated than either of the two discussed above. This is, of course, not a new finding---it has been reported since practically the earliest cloud penetrations by instrumented aircraft. It does, however, present a problem when specifying a cloud "unit" for which a physical characteristic is to be determined. In Fig. 3, virtually all of the variables indicate that the visual cloud was multi-cellular. In many cases, however, this is not true; whereas cellular structure may be indicated in the water distribution, it might not be easily seen in the variations of other parameters. In the tabulations that follow, the visual cloud was broken up into sub-elements whenever these were delimited in the variations of most parameters. Thus, in Fig. 3, the visual cloud was broken into three cloud units in the analysis.

The average value of the cloud water (W_c) and precipitation water (W_p) was calculated for each cloud unit and the cloud water fraction (W_c/W_T) was defined as the ratio of the averages of cloud water content and total water content (W_T). A total of 123 cloud units were studied, distributed among the flights as shown in Table 1.

Population Statistics

In Fig. 4 is shown the frequency of occurrence of cloud water fractions of various magnitudes for the total sample and for a sub-sample in which the

total water content was greater than the adiabatic water content, W_A, the theoretical maximum.

In none of the cloud units was the water dispersed totally in small drops, although in a few instances this condition was approached, as on two of the cloud units shown in Fig. 3. In about half the cases, only 40% of the water was in the form of cloud droplets. In over 80% of the sample, less than 60% of the condensate in a cloud unit was in the form of cloud droplets. When the average total water, W_T, for cloud unit was greater than the adiabatic value, W_A, the cloud water tended to be a small fraction of W_T.

The bimodality in the frequency distribution is a consequence of the differences in the partition of condensate on the two days with the largest number of clouds. It is believed that this is due to the predominance of different cloud types on the two days and may be an indication of differences in the precipitation forming process.

During Flight 5, which contributed nearly a third of the data sample, the measurements were from air mass Cumulus Congestus and Cumulonimbus Calvus. In all but one cloud penetration on this flight the cloud water represented less than 40% of the total water. In Table 2 are given the sample means and standard deviations of the average total, precipitation, and cloud water contents for each flight. On Flight 5 the sample mean of W_T was larger than for any other flight whereas the mean values of W_c, and of W_c/W_T were smallest. On Flights 17 and 18, when the clouds traversed were associated with squall line thunderstorms, the sample means of W_p and W_T were smaller and the average W_c/W_T was larger than on any other flight. Although to some extent the sample means for Flight 5 are colored by the large fraction of cases with water contents in excess of adiabatic (Table 1), the regressions of W_c on W_T, based only on cloud units in which $W_T < W_a$ (Table 2), support the indication that, at this level at least, the fraction of the condensate in large particles is greater in air mass showers than in squall-line associated cumuli of less than thunderstorm size.

The characteristics of the total water contents and of the cloud-precipitation partition in updraft regions are shown in Fig. 5 and Table 3. Identification of these regions were based on the following criteria: (a) the IVSI measurements indicated an updraft through most of the cloud unit and (b) the maximum rate-of-climb exceeded 2 m/sec. (The maximum rate of controlled climb, with full power, at the traverse altitudes was 1 to 1.5 mps). Fifty-four cloud units met these criteria.

The cloud water and total water for cases of $W_T < W_a$ are fairly highly correlated for the sample as a whole (Table 2). This appears to be true also for updraft areas as can be seen from Fig. 5, in which cloud water is plotted against total water for updraft areas, provided a single flight is considered. A close study of Fig. 5 suggests that regression lines for Flights 17 and 18 would probably have a slope significantly greater than 1, while for Flight 5 it would be close to horizontal. In 15 of the 54 updraft regions (predominately from Flights 5 and 11) the total water was greater than the adiabatic. In

Table 2. Various statistics relating to the water content for the total sample, by flight.

Flt No.	Water Content (g/m^3) All cases W_c Mean	W_c σ	W_p Mean	W_p σ	W_T Mean	W_T σ	W_c fraction All cases W_c/W_T Mean	W_c/W_T σ	Reg. line, W_c on W_T Cases $W_T < W_a$ Intercept	Slope	Corr. Coef. Cases $W_T < W_a$
5	0.85	0.46	4.10	3.66	4.95	4.65	0.23	0.13	0.33	0.18	0.72
11	1.19	0.52	3.17	3.41	4.36	3.53	0.38	0.16	0.31	0.31	0.88
17	1.69	0.78	1.34	1.36	3.03	1.54	0.59	0.18	-0.12	0.64	0.80
18	1.02	0.55	1.95	3.03	2.97	3.00	0.48	0.16	-0.02	0.55	0.92
20	1.23	0.68	2.30	2.28	3.53	2.24	0.43	0.23	0.38	0.31	0.62
All	1.19	0.60	2.66	2.72	3.86	2.77	0.41	0.17	--	--	--

Table 3. Sample means of the cloud and precipitation water contents and cloud water fraction in vigorous updraft areas.

Flt No.	$W_T < W_a$ N	W_c	W_p	W_c/W_T	$W_T > W_a$ N	W_c	W_p	W_c/W_T
5	6	1.03	2.79	0.28	7	1.23	8.93	0.15
11	4	1.46	1.52	0.49	4	1.44	7.97	0.18
17	18	2.16	1.23	0.63	1	1.51	8.08	0.16
18	6	1.50	1.28	0.54	1	1.71	6.27	0.27
20	5	1.61	1.08	0.58	2	2.33	3.48	0.41

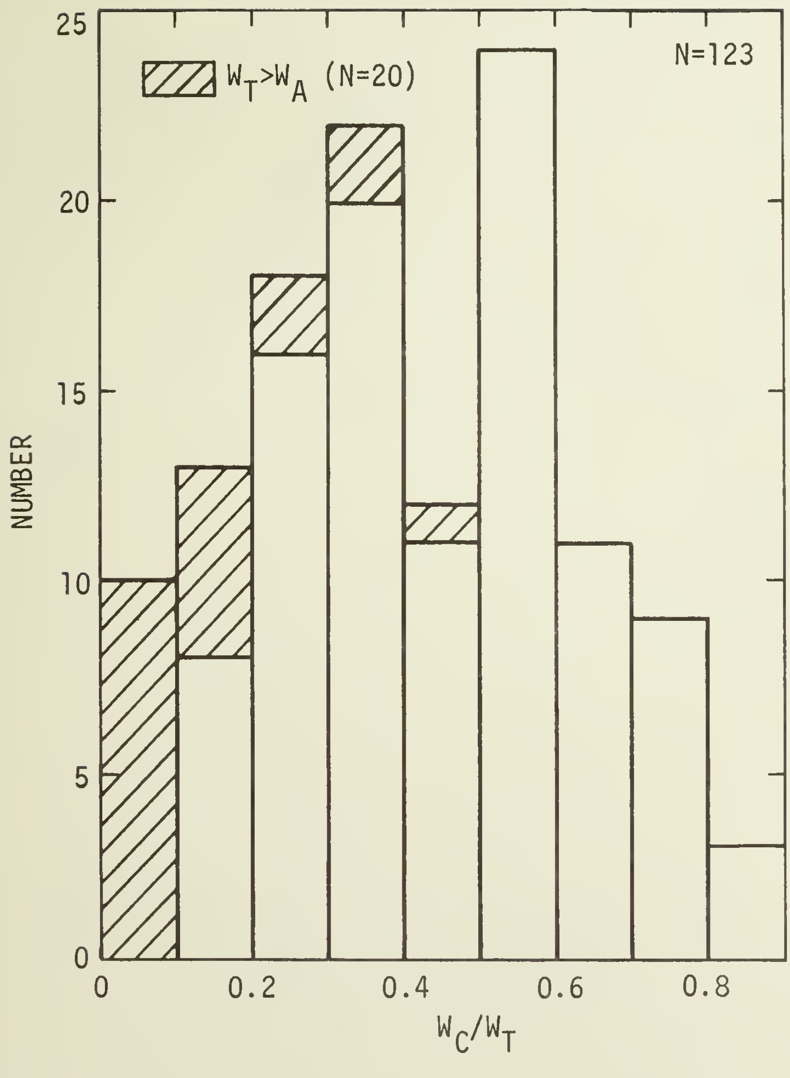

Figure 4. Frequency distribution of the fraction of condensate in cloud droplets (ratio of cloud water to total condensate) in the pooled sample.

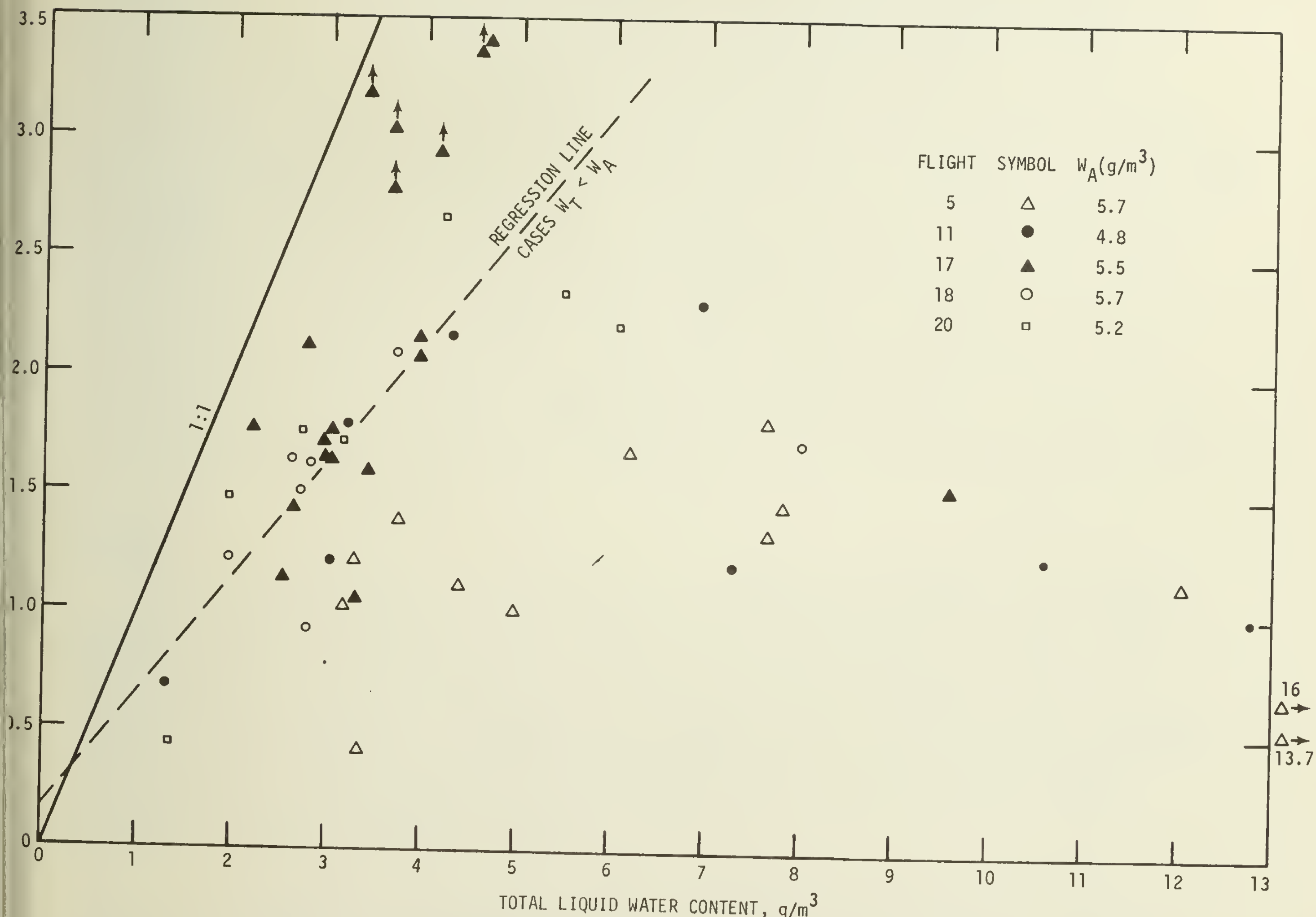

Figure 5. Scatter diagram of average cloud water content versus average total condensate in active updraft regions. The regression line calculated for cloud units in which the average total condensate was less than adiabatic is shown by the dashed line. The points with a vertical arrow near the top were cases in which the cloud water instrument "saturated" for a short interval the point is plotted at a "best" estimate.

the scatter diagram in Fig. 5, all of the points for which $W_T > 5$ gm/m^3 were in the latter group. The scatter for updraft areas with $W_T > W_a$ suggests an inverse relationship between W_c and W_T.

In Table 3 are listed the sample means of the cloud and precipitation water content and the cloud water fraction for the updraft areas. These may be compared with the sample means for the total sample, listed in Table 2. The comparison indicates that, in updraft areas in which the total water is less than adiabatic, the precipitation water content is less than it is in other cloud areas and the cloud water content and cloud water fraction are significantly larger. This is what would be expected from arguments relating to the time required for significant precipitation to develop due to coalescence. When total water content in an updraft is greater than adiabatic, the net flux divergence of water by sedimentation through the air as it ascended must have been positive and the precipitation water content should be larger than in other cloud areas. It can be seen from Tables 2 and 3 that this was indeed true for such updrafts---average precipitation water in updrafts with $W_T > W_a$ was larger by a factor of two or more on most flights. Moreover, the average cloud water content also tended to be larger so that the increase in total water was due to an increase in the amounts in both segments of the bulk water. As would be expected, in-cloud units in which the water content is dominated by sedimentation the cloud water fraction is smaller than in other cloud areas.

Summary

This "first look" at the partition of condensate between cloud droplets and precipitation particles points up, once again, the existence of a very active process of coalescence in clouds in the middle west. In addition it indicates that the efficiency of coalescence may vary greatly either as a function of day or as a function of cloud type. As the research continues the sample will be materially enlarged by the addition of data from other flights. Future analysis will explore the differences between cloud types and the influences of environmental factors, and specific cloud parameters such as diameter, updraft velocity, buoyancy, etc.

Acknowledgments. The author wishes to express her appreciation to Dr. Robert Ruskin of the Naval Research Laboratory for the loan of the total water content meter, to the various members of the staff at the Pennsylvania State University for their cooperation and to Mr. T. Flach, formerly on the staff of the Illinois State Water Survey for his engineering assistance.

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APPENDIX 1

An analysis of the personnel that were involved in this program in FY-74 and the amount of their involvement appears below.

Salary Support from State of Illinois

	Percent Time	Begin	End
S. A. Changnon	5%	August	July
R. G. Semonin	2%	August	July
F. A. Huff	2%	August	July

Salary Support from Bureau of Reclamation

B. Ackerman	50%	August	July
T. Flach	100%	August	October
O. Anderson	100%	August only	
Y. Liu	40%	September	July